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Reflection using the derivability conditions

Seán Matthews* Alex K. Simpson†

Dedicated to the memory of Roberto Magari

Abstract

We extend arithmetic with a new predicate, Pr , giving axioms for Pr based on first-order versions of Löb’s derivability conditions. We hoped that the addition of a reflection schema mentioning Pr would then give a non-conservative extension of the original arithmetic theory. The paper investigates this possibility. It is shown that, under special conditions, the extension is indeed non-conservative. However, in general such extensions turn out to be conservative.

1 Introduction

In any recursively axiomatized theory of arithmetic, T , one can follow Gödel’s construction to obtain a ‘provability predicate’, a Σ_1 -formula $Bew_T(x)$ such that $Bew_T(\ulcorner A \urcorner)$ is true if and only if $T \vdash A$, where $\ulcorner A \urcorner$ is the Gödel number of the formula A . Moreover, if T is sufficiently strong then Bew_T satisfies the following predicate (or ‘uniform’) versions of Löb’s derivability conditions [7]:

- (D1) $\text{if } T \vdash \forall x A \text{ then } T \vdash \forall x Bew_T(\ulcorner A\langle x \rangle \urcorner),$
- (D2) $T \vdash \forall x (Bew_T(\ulcorner (A \rightarrow B)\langle x \rangle \urcorner) \rightarrow (Bew_T(\ulcorner A\langle x \rangle \urcorner) \rightarrow Bew_T(\ulcorner B\langle x \rangle \urcorner))),$
- (D3) $T \vdash \forall x (Bew_T(\ulcorner A\langle x \rangle \urcorner) \rightarrow Bew_T(\ulcorner Bew_T(\ulcorner A\langle x \rangle \urcorner)\langle x \rangle \urcorner)),$

where we write $\ulcorner A\langle x \rangle \urcorner$ for a term with a free variable x ‘disquoting’ any occurrence of x in A (see Section 2). Solovay, [9], showed that the original propositional versions of the derivability conditions identify all the valid ‘modal’ schematic properties of Bew_T (the other modal axiom, the formalization of Löb’s theorem, is derivable from (D1)–(D3) using the diagonalization lemma). Although the first-order derivability conditions above do not capture all the valid first-order schematic properties of Bew_T (see [2]), they do isolate a natural class of ‘modal’ properties satisfied by Bew_T .

All the aforementioned work treats the derivability conditions as *descriptive* in that their purpose is to describe properties of the Bew predicate. In this paper we consider them in an alternative *prescriptive* rôle. We define a language, \mathcal{L}' , by adding a new unary predicate symbol, Pr , to the original language \mathcal{L} . Then we define an \mathcal{L}' -theory, T' , as

*Max-Planck-Institut für Informatik, Saarbrücken, Germany <sean@mpi-sb.mpg.de>.

†Dept. of Computer Science, University of Edinburgh, Scotland <Alex.Simpson@dcs.ed.ac.uk>.

the least theory containing T that is closed under the following analogues of (D1)–(D3):

- (C1) $\text{if } T' \vdash \forall x A \text{ then } T' \vdash \forall x Pr(\ulcorner A \langle x \rangle \urcorner),$
(C2) $T' \vdash \forall x (Pr(\ulcorner (A \rightarrow B) \langle x \rangle \urcorner) \rightarrow Pr(\ulcorner A \langle x \rangle \urcorner) \rightarrow Pr(\ulcorner B \langle x \rangle \urcorner)),$
(C3) $T' \vdash \forall x (Pr(\ulcorner A \langle x \rangle \urcorner) \rightarrow Pr(\ulcorner Pr(\ulcorner A \langle x \rangle \urcorner) \langle x \rangle \urcorner)),$

where we assume that Gödel numbering has been extended to \mathcal{L}' . It is natural to ask how much of the behaviour of $Bew_{T'}$ is forced upon Pr by the satisfaction of (C1)–(C3).

As remarked in Boolos and Jeffrey [1, p. 185], there are many ‘predicates’ other than Bew_T that satisfy (D1)–(D3); for example, the predicate expressing the property of being (the Gödel number of) a well-formed formula. Therefore it does not hold that $T' \vdash \forall x (Pr(x) \rightarrow Bew_{T'}(x))$. We shall see below that the converse implication fails too.

However, it occurred to us to consider the effect of adjoining the following analogue of the uniform reflection schema to T' :

$$(R) \quad \forall x (Pr(\ulcorner A \langle x \rangle \urcorner) \rightarrow A).$$

The question we were interested in was whether $T' + R$ is a non-conservative extension of the original theory T .

The possibility that $T' + R$ might not be conservative over T was initially plausible for the following reason. There is an evident ‘intended’ interpretation of T' in T under which Pr is (modulo some mapping of Gödel numbers) translated as Bew_T . Although this interpretation can be used to prove that T' is a conservative extension of T , it cannot be used to show that $T' + R$ is. Furthermore, no other translation of Pr can be used for this purpose either (Theorem 1).

On the other hand, the same interpretation can be used to establish that any \mathcal{L} -formula entailed by $T' + R$ is a theorem in the theory obtained by extending T with its uniform reflection schema:

$$(Rfn) \quad \forall x (Bew_T(\ulcorner A \langle x \rangle \urcorner) \rightarrow A).$$

By Gödel’s second incompleteness theorem, $T' + R$ is a non-conservative extension of T . Our initial hope was that $T' + R$ might be a (necessarily conservative) extension of $T + Rfn$.

This possibility would be of practical interest. If $T' + R$ were an extension of $T + Rfn$, then the definition of $T' + R$ would provide a feasible way of extending the reasoning powers of T without having to go through the laborious construction of Gödel’s Bew_T predicate (although admittedly the definition of $T' + R$ does still require a Gödel numbering of formulae). Unfortunately, it turns out that $T' + R$ is always conservative over T (Theorem 2). (This shows that, as claimed above, $T' \not\vdash \forall x (Bew_{T'}(x) \rightarrow Pr(x))$.) Thus our construction of $T' + R$ does not give the *general* method of achieving a non-conservative extension of T that we hoped for.

Nevertheless, a slight and natural modification of the construction of $T' + R$ does lead to a non-conservative extension in one notable case. Since $Pr(t)$ is intended to mimic $Bew_T(t)$ it ought to be treated as a Σ_1 -formula. So if T supports induction over Σ_1 -formulae then it is reasonable to include induction over atomic formulae of the form $Pr(t)$ in T' . In this case $T' + R$ provides full induction over formulae of \mathcal{L}' , and thus contains Peano Arithmetic (Theorem 3). So for any T containing Σ_1 -induction but not full induction, a non-conservative extension can be obtained by our method.

Unfortunately, the non-conservative effect does not extend beyond Peano Arithmetic. Since Peano Arithmetic supports induction over arbitrary formulae of \mathcal{L} it is natural to allow induction over arbitrary formulae of \mathcal{L}' in T' . However, even allowing such induction, if T is Peano Arithmetic then $T' + R$ is conservative over T (Theorem 4).

The paper is structured as follows. In Section 2 we give the technical background to our work. In Section 3 we give a semantic proof that, in general, $T' + R$ is conservative over T . In Section 4 we consider extending induction to the new language, proving the non-conservativity result for arithmetic with Σ_1 -induction and the conservativity result for Peano Arithmetic. Finally, Section 5 contains some concluding remarks.

2 Preliminaries

Throughout the paper we work, for convenience, with the language, \mathcal{L} , of Primitive Recursive Arithmetic (*PRA*) [4]. Thus when we refer to Peano Arithmetic (*PA*) we mean a definitional extension in \mathcal{L} of the usual Peano Arithmetic (which is in the language of elementary arithmetic). As in Section 1, \mathcal{L}' is the language obtained by adding a new unary predicate symbol, Pr , to \mathcal{L} .

A Gödel-numbering of \mathcal{L}' is an injective mapping from \mathcal{L}' into the natural numbers. We assume some such mapping. We denote the number standing for a formula A of \mathcal{L}' by $\ulcorner A \urcorner$, and similarly for terms, etc. We assume that all the relevant operations and predicates on formulae/terms are primitive recursive. In particular there is a primitive recursive function $sub(\cdot, \cdot, \cdot)$, such that for any formula A (or term t), and number n :

$$sub(\ulcorner A \urcorner, \ulcorner x \urcorner, n) = \ulcorner A[\bar{n}/x] \urcorner$$

where \bar{n} is the numeral $s^n(0)$. We write $\ulcorner A(t) \urcorner$ as an abbreviation for $sub(\ulcorner A \urcorner, \ulcorner x \urcorner, t)$. The restriction of $\ulcorner \cdot \urcorner$ to \mathcal{L} gives us also a Gödel-numbering of \mathcal{L} .

Let T be any consistent, recursively axiomatized theory in \mathcal{L} extending *PRA* (thus T supports quantifier-free induction). Let $Bew_T(x)$ be Gödel's provability predicate for T . As T extends *PRA*, the formula Bew_T does indeed satisfy the properties (D1)–(D3) of Section 1. Define the \mathcal{L}' -theory T' as in Section 1.

Proposition 1 *T' is a conservative extension of T .*

Proof. We define a translation $(\cdot)^*$ from formulae of \mathcal{L}' to formulae of \mathcal{L} . By the second recursion theorem, there is a number r such that (writing $\{r\}$ for the r -th partial recursive function):

$$\{r\}(\ulcorner A \urcorner) = \ulcorner A^* \urcorner$$

where $(\cdot)^*$ commutes with connectives and quantifiers and is defined on atomic formulae by:

$$\begin{aligned} P(t_1, \dots, t_n)^* &= P(t_1, \dots, t_n) \quad (\text{where } P \neq Pr) \\ Pr(t)^* &= \exists y (T(\bar{r}, t, y) \wedge Bew_T(U(y))) \end{aligned}$$

(here T and U are Kleene's primitive-recursive T predicate and result-extraction function). By definition $\{r\}$ is primitive recursive, so there is a function symbol, $star$, such

that, by the formalized recursion theorem and quantifier-free induction:

- (1) $T \vdash \forall x \exists y (T(\bar{r}, x, y) \wedge U(y) = \text{star}(x)),$
- (2) $T \vdash \forall x (\text{star}(\ulcorner A \langle x \rangle \urcorner) = \ulcorner A^* \langle x \rangle \urcorner).$

We now show that for all \mathcal{L}' -formulae A , if $T' \vdash A$ then $T \vdash A^*$; which, since $(\cdot)^*$ is the identity on \mathcal{L} -formulae, establishes the desired conservativity result. The proof is a straightforward induction on the closure conditions of T' :

- (C1) Assume that $T' \vdash \forall x A$. By the induction hypothesis we have that $T \vdash (\forall x A)^*$, and therefore that $T \vdash \forall x A^*$. We need to show that $T \vdash (\forall x \text{Pr}(\ulcorner A \langle x \rangle \urcorner))^*$; i.e., that

$$T \vdash \forall x \exists y (T(\bar{r}, \ulcorner A \langle x \rangle \urcorner, y) \wedge \text{Bew}_T(U(y))).$$

However, $T \vdash \forall x y z w (T(x, y, z) \wedge T(x, y, w)) \rightarrow z = w$. Therefore, by (1) and (2), the above formula is equivalent to $T \vdash \forall x \text{Bew}_T(\ulcorner A^* \langle x \rangle \urcorner)$. And this, in turn, follows from (D1) and the fact that $T \vdash \forall x A^*$.

- (C2) We have to show that

$$T \vdash (\forall x \text{Pr}(\ulcorner (A \rightarrow B) \langle x \rangle \urcorner) \rightarrow (\text{Pr}(\ulcorner A \langle x \rangle \urcorner) \rightarrow \text{Pr}(\ulcorner B \langle x \rangle \urcorner)))^*$$

which, in the same way as (C1) above, reduces to

$$T \vdash \forall x (\text{Bew}_T(\ulcorner (A \rightarrow B)^* \langle x \rangle \urcorner) \rightarrow \text{Bew}_T(\ulcorner A^* \langle x \rangle \urcorner) \rightarrow \text{Bew}_T(\ulcorner B^* \langle x \rangle \urcorner)),$$

an instance of (D2).

- (C3) Similar to (C2) only making use of (D3) instead. □

Proposition 2 *For any \mathcal{L} -formula A , if $T' + R \vdash A$ then $T + Rfn \vdash A$.*

Proof. Let $(\cdot)^*$ be the translation from \mathcal{L}' to \mathcal{L} defined in the last proof. We already know that if $T' \vdash A$ then $T \vdash A^*$ and hence $T + Rfn \vdash A^*$. So we need only show that $T + Rfn \vdash R^*$. However, as in the proof above, this translates to showing that:

$$T + Rfn \vdash \forall x (\text{Bew}_T(\ulcorner A^* \langle x \rangle \urcorner) \rightarrow A^*),$$

which is an instance of Rfn . □

The above translation cannot be used to prove the conservativity of $T' + R$ over T , because it is not in general the case that $T \vdash \forall x (\text{Bew}_T(\ulcorner A^* \langle x \rangle \urcorner) \rightarrow A^*)$. One might wonder whether there is a cleverer translation that works instead. We now give a quite general proof that in fact there is none.

We consider a general notion of translation useful for proving conservativity. A *retraction* of \mathcal{L}' onto \mathcal{L} is a function, $(\cdot)^\dagger$, from \mathcal{L}' -formulae to \mathcal{L} -formulae that: commutes with connectives and quantifiers; maps atomic formulae in \mathcal{L} to themselves; and maps $\text{Pr}(t)$ to $H(t)$, where $H(x)$ is some fixed \mathcal{L} -formula. (It is a retraction in the appropriate category of languages and translations.) Clearly $(\cdot)^\dagger$ is determined by the choice of $H(x)$. Note that the translation, $(\cdot)^*$, used in the above proofs is the retraction determined by the formula $\exists y (T(\bar{r}, x, y) \wedge \text{Bew}_T(U(y)))$.

Let S be any \mathcal{L} -theory and S' be any \mathcal{L}' -theory extending S . A *retraction* of S' onto S is a retraction, $(\cdot)^\dagger$, from \mathcal{L}' to \mathcal{L} such that, for any \mathcal{L}' -formula A , it holds that $S' \vdash A$ implies $S \vdash A^\dagger$. (It is a retraction in the appropriate category of theories and interpretations.) It is clear that the existence of a retraction from S' to S implies that S' is a conservative extension of S . Indeed the proof of Proposition 1 worked by establishing that $(\cdot)^*$ is a retraction of T' onto T . The impossibility of obtaining a similar translational proof of the conservativity of $T' + R$ over T is given by:

Theorem 1 *There is no retraction of $T' + R$ onto T .*

Proof. Suppose, for contradiction, that $(\cdot)^\dagger$ is a retraction of $T' + R$ onto T in which Pr is translated to $H(x)$. By the diagonalization lemma, there is an \mathcal{L} -sentence A such that:

$$(3) \quad T \vdash A \leftrightarrow \neg H(\ulcorner A \urcorner).$$

However, we claim that:

$$(4) \quad \text{if } T \vdash A \text{ then } T \vdash H(\ulcorner A \urcorner),$$

$$(5) \quad T \vdash H(\ulcorner A \urcorner) \rightarrow A.$$

To see that (4) holds, suppose that $T \vdash A$. Then $T' \vdash A$. So, by (C1), it follows that $T' \vdash Pr(\ulcorner A \urcorner)$. Therefore $T \vdash (Pr(\ulcorner A \urcorner))^\dagger$. So $T \vdash H(\ulcorner A \urcorner)$ as required. For (5), we have that $T' + R \vdash Pr(\ulcorner A \urcorner) \rightarrow A$. So $T \vdash (Pr(\ulcorner A \urcorner) \rightarrow A)^\dagger$. Thus indeed $T \vdash H(\ulcorner A \urcorner) \rightarrow A$.

But from (3)–(5) it is easy to derive that T is inconsistent — a contradiction. \square

This proof is similar to Montague's proof of the inconsistency of giving syntactic interpretations to certain modal logics [8].

3 The general conservativity proof

Theorem 1 gives hope that $T' + R$ might be non-conservative over T . Unfortunately, this turns out not to be the case. The main theorem of this section is:

Theorem 2 *$T' + R$ is a conservative extension of T .*

The proof of the theorem involves some analysis of properties of Gödel-numbering when formalized in T . Recall that all the relevant operations and predicates on Gödel-numbers have been assumed to be primitive recursive. More specifically, we require primitive recursive ‘constructors’ for all function symbols, predicate symbols, connectives and quantifiers, which can be used to assemble terms and formulas. As T supports quantifier-free induction, each constructor is provably injective. Furthermore it is provable in T that the Gödel-number of a compound term/formula has a unique decomposition into the components out of which it is built. We also require a primitive recursive function $free-in(\cdot, \cdot)$, such that $free-in(\ulcorner A \urcorner, \ulcorner x \urcorner)$ if and only if x is free in A (and similarly for terms). Again, quantifier-free induction suffices to ensure that:

$$(S1) \quad T \vdash \ulcorner A[s(x)/x] \urcorner = \ulcorner A \urcorner,$$

$$(S2) \quad T \vdash \neg free-in(\ulcorner A \urcorner, \ulcorner x \urcorner) \rightarrow \ulcorner A \urcorner = \ulcorner A \urcorner,$$

$$(S3) \quad T \vdash (free-in(\ulcorner A \urcorner, \ulcorner x \urcorner) \wedge \ulcorner A \urcorner = \ulcorner A \urcorner) \rightarrow y = z,$$

$$(S4) \quad T \vdash (free-in(\ulcorner t \urcorner, \ulcorner x \urcorner) \wedge \ulcorner t \urcorner \neq \ulcorner x \urcorner \wedge y \leq z) \rightarrow \ulcorner x \urcorner \neq \ulcorner t \urcorner.$$

The meanings of (S1)–(S3) are clear (and, of course, analogous properties hold for substitution in terms). The more cumbersome (S4) reflects the fact that if t is different from, but contains, x and $m \leq n$, then \overline{m} is different from $t[\overline{n}/x]$ (since the former is a strict subterm of the latter).

Theorem 2 will be proved semantically. Let $\mathfrak{M} = (D, \leq, 0, s, \dots)$ be an arbitrary model of T . We extend \mathfrak{M} to a \mathcal{L}' -structure, \mathfrak{M}' , by defining, for $d \in D$:

$$\begin{aligned} Pr(d) \quad \text{if} \quad & \text{there exists an } \mathcal{L}'\text{-formula } A \text{ and an element } d' \in D \text{ such that} \\ & d = \ulcorner A\langle d' \rangle \urcorner \text{ and } T' \vdash \forall x A. \end{aligned}$$

We shall prove a sequence of results aiming to show that \mathfrak{M}' is a model of $T' + R$.

First we make some useful observations. If x occurs free in A then, by (S3), the function $x \mapsto \ulcorner A\langle x \rangle \urcorner$ tends to infinity. Moreover, for any n , there exists m such that $T \vdash \forall x \geq m \ulcorner A\langle x \rangle \urcorner \geq n$ (by quantifier free induction). Thus if d is any non-standard element in D then the element $\ulcorner A\langle d \rangle \urcorner$ is also non-standard. On the other hand, if x does not occur free in A then, by (S2), $\ulcorner A\langle d \rangle \urcorner$ is standard and equal to $\ulcorner A \urcorner$.

Lemma 3 *If $d \in D$ is non-standard, $d \leq d' \in D$ and $\ulcorner A\langle d \rangle \urcorner = \ulcorner B\langle d' \rangle \urcorner$ then there exists n such that A is syntactically identical to $B[s^n(x)/x]$ (notation $A \equiv B[s^n(x)/x]$).*

Proof. The proof is by induction on the structure of B . Suppose that $d \in D$ is non-standard and $d \leq d' \in D$.

We first show, by induction on the structure of terms t , that if $\ulcorner t'\langle d \rangle \urcorner = \ulcorner t\langle d' \rangle \urcorner$ then:

1. if x does not occur free in t , then $t' \equiv t$;
2. if x occurs free in t then there exists n such that $d' = s^n(d)$ and $t' \equiv t[s^n(x)/x]$.

Suppose the term is a variable, y , different from x , and $\ulcorner t'\langle d \rangle \urcorner = \ulcorner y\langle d' \rangle \urcorner$. Now x is not free in y so, by (S2), $\ulcorner y\langle d' \rangle \urcorner = \ulcorner y \urcorner$ and is standard. Thus $\ulcorner t'\langle d \rangle \urcorner$ is standard, which implies that x does not occur free in t' . So $\ulcorner t'\langle d \rangle \urcorner = \ulcorner t' \urcorner$. Therefore, by the injectivity of Gödel numbering, $t' \equiv y$ as required.

Suppose the term is x and $\ulcorner t'\langle d \rangle \urcorner = \ulcorner x\langle d' \rangle \urcorner$. We prove, by induction on the structure of t' , that there exists n such that $d' = s^n(d)$ and $t' \equiv s^n(x)$. First, t' cannot be a variable y different from x because then $\ulcorner t'\langle d \rangle \urcorner$ would be standard whereas $\ulcorner x\langle d' \rangle \urcorner$ is non-standard. If t' is x then we are done with $n = 0$, as $d = d'$ by (S3). Lastly, suppose that t' is of the form $f'(t'_1, \dots, t'_h)$ (with h possibly zero). Now $d' \in D$ is non-standard so it has a predecessor $d'' \in D$. Thus $\ulcorner x\langle d' \rangle \urcorner = \ulcorner x\langle s(d'') \rangle \urcorner = \ulcorner s(x)\langle d'' \rangle \urcorner$, the last equality by (S1). But then $\ulcorner t'\langle d \rangle \urcorner = \ulcorner s(x)\langle d'' \rangle \urcorner$. So, by the formalized injectivity of Gödel numbering, t' is of the form $s(t'')$ for some t'' such that $\ulcorner t''\langle d \rangle \urcorner = \ulcorner x\langle d'' \rangle \urcorner$. Then, by the induction hypothesis, there exists n such that $d'' = s^n(d)$ and $t'' \equiv s^n(x)$. Thus $n + 1$ is the number required as $d' = s^{n+1}(d)$ and $t' \equiv s^{n+1}(x)$.

Suppose that the term is $f(t_1, \dots, t_k)$ (where k is possibly zero) and $\ulcorner t'\langle d \rangle \urcorner = \ulcorner f(t_1, \dots, t_k)\langle d' \rangle \urcorner$. Then t' cannot be a variable y different from x . If t' is x then x must occur free in some t_i (otherwise $\ulcorner f(t_1, \dots, t_k)\langle d' \rangle \urcorner$ would be standard). However, $d \leq d'$ so, by (S4), $\ulcorner x\langle d \rangle \urcorner \neq \ulcorner f(t_1, \dots, t_k)\langle d' \rangle \urcorner$, a contradiction. So t' must be of the form $f'(t'_1, \dots, t'_h)$. But then, by formalized injectivity, we have that $f \equiv f'$. So $h = k$ and, for all i ($1 \leq i \leq k$) $\ulcorner t'_i\langle d \rangle \urcorner = \ulcorner t_i\langle d' \rangle \urcorner$. If x does not occur free in any t_i then, by the induction hypothesis, $t'_i \equiv t_i$ for all i and thus $t' \equiv f(t_1, \dots, t_k)$ as required. If x

does occur free in some t_i then, by the induction hypothesis, there exists n such that $d' = s^n(d)$ and, for all i , $t'_i \equiv t_i[s^n(x)/x]$. So indeed $t' \equiv f(t_1, \dots, t_k)[s^n(x)/x]$.

It remains only to extend the induction to formulae. One proves, by induction on the structure of B , that $\ulcorner A\langle d \rangle \urcorner = \ulcorner B\langle d' \rangle \urcorner$ implies that if x does not occur free in B then $A \equiv B$ and if x does occur free in B then there exists n such that $d' = s^n(d)$ and $A \equiv B[s^n(x)/x]$. The straightforward argument, similar to the case for $f'(t'_1, \dots, t'_h)$ and $f(t_1, \dots, t_k)$ above, is omitted. The result follows. \square

Lemma 4

1. If $d \in D$ is standard then $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$ if and only if $T' \vdash A[\bar{d}/x]$.
2. If $d \in D$ is non-standard then $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$ if and only if there exists n such that $T' \vdash \forall x(A[s^n(x)/x])$.

Proof.

1. Suppose $d \in D$ is standard and $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. Then $\ulcorner A[\bar{d}/x] \urcorner = \ulcorner A\langle d \rangle \urcorner = \ulcorner B\langle d' \rangle \urcorner$ for some $d' \in D$ and B such that $T' \vdash \forall x B$ (by the definition of the extension of Pr in \mathfrak{M}'). Now if d' is standard then $T' \vdash B[\bar{d'}/x]$ and $\ulcorner A[\bar{d}/x] \urcorner = \ulcorner B[\bar{d'}/x] \urcorner$ so $A[\bar{d}/x] \equiv B[\bar{d'}/x]$. Thus indeed $T' \vdash A[\bar{d}/x]$. If, however, d' is non-standard then x cannot occur free in B . Therefore $T' \vdash B$ and $\ulcorner A[\bar{d}/x] \urcorner = \ulcorner B \urcorner$ so $A[\bar{d}/x] \equiv B$. Thus again $T' \vdash A[\bar{d}/x]$ as required.

Conversely, suppose that $T' \vdash A[\bar{d}/x]$. Then trivially $T' \vdash \forall x A[\bar{d}/x]$. It follows that $\mathfrak{M}' \models \text{Pr}(\ulcorner A[\bar{d}/x] \urcorner)$. Thus indeed $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$.

2. Suppose that $d \in D$ is non-standard, and that $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. Then $\ulcorner A\langle d \rangle \urcorner = \ulcorner B\langle d' \rangle \urcorner$ for some $d' \in D$ and B such that $T' \vdash \forall x B$. If $d \leq d'$ then, by Lemma 3, $A \equiv B[s^m(x)/x]$ for some m . So clearly $T' \vdash \forall x A$, and the n we are required to find is zero. If $d' < d$ and d' is non-standard then, by Lemma 3, $A[s^n(x)/x] \equiv B$ for some n . But then we have found an n such that $T' \vdash \forall x A[s^n(x)/x]$. Lastly, if d' is standard then $\ulcorner B\langle d' \rangle \urcorner$ is standard, so x cannot occur free in A . Thus $A \equiv B[\bar{d'}/x]$ and $T' \vdash B[\bar{d'}/x]$. Therefore $T' \vdash \forall x A$ and again n is zero.

Conversely, suppose there exists n such that $T' \vdash \forall x A[s^n(x)/x]$. As d is non-standard, there exists $d' \in D$ such that $d = s^n(d')$. By the definition of the extension of Pr , $\mathfrak{M}' \models \text{Pr}(\ulcorner A[s^n(x)/x]\langle d' \rangle \urcorner)$. But, by (S1), $\ulcorner A\langle d \rangle \urcorner = \ulcorner A[s^n(x)/x]\langle d' \rangle \urcorner$. So indeed $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. \square

Proposition 5 \mathfrak{M}' is a model of T' .

Proof. We must show that \mathfrak{M}' validates (C1)–(C3).

- (C1) Suppose $T' \vdash \forall x A$ and $d \in D$. Then it is immediate from the definition of the extension of Pr in \mathfrak{M}' that $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$ as required.
- (C2) Suppose $d \in D$, $\mathfrak{M}' \models \text{Pr}(\ulcorner (A \rightarrow B)\langle d \rangle \urcorner)$ and $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. If d is standard then, by Lemma 4(1), $T' \vdash (A \rightarrow B)[\bar{d}/x]$ and $T' \vdash A[\bar{d}/x]$. So $T' \vdash B[\bar{d}/x]$ whence, by Lemma 4(1), $\mathfrak{M}' \models \text{Pr}(\ulcorner B\langle d \rangle \urcorner)$ as required. If d is non-standard then, by Lemma 4(2), there exists m such that $T' \vdash \forall x (A \rightarrow B)[s^m(x)/x]$ and there exists m' such that $T' \vdash \forall x A[s^{m'}(x)/x]$. Therefore $T' \vdash \forall x B[s^n(x)/x]$ where n is the maximum of m and m' . So, by Lemma 4(2), $\mathfrak{M}' \models \text{Pr}(\ulcorner B\langle d \rangle \urcorner)$ as required.

(C3) Suppose that $d \in D$ and $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. We omit the easy argument if d is standard. If d is non-standard then, by Lemma 4(2), there exists n such that $T' \vdash \forall x A[s^n(x)/x]$. Whence, by (C1), $T' \vdash \forall x \text{Pr}(\ulcorner A[s^n(x)/x] \urcorner)$. Now, by n applications of (S1), $T' \vdash \forall x (\text{Pr}(\ulcorner A\langle s^n(x) \rangle \urcorner))$. So, by Lemma 4(2), it follows that $\mathfrak{M}' \models \text{Pr}(\ulcorner \text{Pr}(\ulcorner A\langle x \rangle \urcorner) \urcorner)$ as required. \square

We now have a second proof of Proposition 1. We have shown that any model \mathfrak{M} of T extends to a model \mathfrak{M}' of T' . It follows that T' is a conservative extension of T .

Proposition 6 \mathfrak{M}' is a model of $T' + R$.

Proof. We need only verify R. Suppose then that $d \in D$ and $\mathfrak{M}' \models \text{Pr}(\ulcorner A\langle d \rangle \urcorner)$. If d is standard then, by Lemma 4(1), $T' \vdash A[\bar{d}/x]$. Thus, by Proposition 5, $\mathfrak{M}' \models A[d/x]$ as required. If, however, d is non-standard then, by Lemma 4(2), there exists n such that $T' \vdash \forall x (A[s^n(x)/x])$. By Proposition 5, $\mathfrak{M}' \models \forall x (A[s^n(x)/x])$. But d is non-standard, so there exists $d' \in D$ such that $d = s^n(d')$. Therefore $\mathfrak{M}' \models A[d/x]$ as required. \square

We have shown that any model of T extends to a model of $T' + R$. This completes the proof of Theorem 2.

4 Extending induction to \mathcal{L}'

The conservativity result of the last section is very general, as the proof works for an arbitrary T extending PRA . Nevertheless, one important possibility has been overlooked: that of extending induction to the language \mathcal{L}' . However, the rules of how one ought to do this are not immediately clear. For example, if T is PRA then it only has induction over quantifier-free formulae. Given that we are thinking of Pr as a Σ_1 -formula in disguise, it does not seem reasonable to give T' any instances of induction not already available in PRA . Thus although uniform reflection together with PRA gives PA , there is no analogous result using T' and R .

The situation becomes a good deal more interesting if we consider PRA together with Σ_1 -induction as the initial theory. We shall refer to this theory as $I\Sigma_1$.

With $I\Sigma_1$ as the base theory it seems reasonable to give the extended theory induction over some appropriate analogue of Σ_1 in \mathcal{L}' . To this end, we extend the arithmetical hierarchy to \mathcal{L}' . We define sets Σ'_n, Π'_n ($1 \leq n$) as the least sets closed under:

1. $\Sigma'_n \subseteq \Sigma'_{n+1}, \Pi'_{n+1}$ and $\Pi'_n \subseteq \Sigma'_{n+1}, \Pi'_{n+1}$
2. If P is not Pr then $P(t_1, \dots, t_n) \in \Sigma'_1, \Pi'_1$.
3. $\text{Pr}(t) \in \Sigma'_1$.
4. If $A, B \in \Sigma'_n$ then $A \wedge B, \exists x A \in \Sigma'_n$ and $\neg A \in \Pi'_n$.
5. If $A, B \in \Pi'_n$ then $A \wedge B, \forall x A \in \Pi'_n$ and $\neg A \in \Sigma'_n$.

The motivation is that Pr is supposed to be emulating a Σ_1 (but not Π_1) formula.

We now give the extended theory, $I\Sigma'_1$, the evident definition: $I\Sigma'_1$ is the smallest \mathcal{L}' -theory containing $I\Sigma_1$ and Σ'_1 -induction and closed under (C1)–(C3). Again we consider adding the analogue of uniform reflection, R . This time we do get the desired non-conservativity.

Theorem 3 $I\Sigma'_1 + R$ contains PA .

Proof. Suppose that $I\Sigma'_1 \vdash A[0/x]$ and $I\Sigma'_1 \vdash \forall x (A \rightarrow A[s(x)/x])$. Applying (C1) we get that $I\Sigma'_1 \vdash Pr(\ulcorner A[0/x] \urcorner)$ and $I\Sigma'_1 \vdash \forall x Pr(\ulcorner A \rightarrow A[s(x)/x] \urcorner)$. The former gives immediately:

$$I\Sigma'_1 \vdash Pr(\ulcorner A \langle 0 \rangle \urcorner).$$

The latter gives, by (C2), $I\Sigma'_1 \vdash \forall x (Pr(\ulcorner A \langle x \rangle \urcorner) \rightarrow Pr(\ulcorner A[s(x)/x] \langle x \rangle \urcorner))$ whence, by (S1):

$$I\Sigma'_1 \vdash \forall x (Pr(\ulcorner A \langle x \rangle \urcorner) \rightarrow Pr(\ulcorner A \langle s(x) \rangle \urcorner)).$$

We can now apply Σ'_1 -induction to derive $I\Sigma'_1 \vdash \forall x Pr(\ulcorner A \langle x \rangle \urcorner)$. Therefore, by one application of R , we have that $I\Sigma'_1 + R \vdash \forall x A$.

It is now easy to see that $I\Sigma'_1 + R$ derives induction for any \mathcal{L}' -formula, B . Just apply the above argument to the formula:

$$A \equiv (B[0/x] \wedge \forall y (B[y/x] \rightarrow B[s(y)/x])) \rightarrow B.$$

The result follows. \square

It is a special case of Lemma 8 below that $I\Sigma'_1 + R$ is actually conservative over PA .

The above argument can be translated back to give an elegant proof, using only (D1), (D2) and (S1), that $I\Sigma_1 + Rfn$ is a theory as strong as PA . Note that condition (C3) was not needed in the proof. Also, R was used only as a rule. We conjecture that if any of (C1), (C2) and R are weakened to their propositional versions then the resulting extension of $I\Sigma_1$ is conservative.

We conclude by showing that the trick used to prove Theorem 3 cannot be generalized to derive stronger principles than full induction. Define PA' to be the least \mathcal{L}' -theory containing PA and induction over every \mathcal{L}' -formula and closed under (C1)–(C3).

Theorem 4 $PA' + R$ is a conservative extension of PA .

We write $I\Sigma_n$ for the \mathcal{L} -theory obtained by extending PRA with Σ_n -induction. Following the definition of $I\Sigma'_1$ above, define $I\Sigma'_n$ to be the least \mathcal{L}' -theory containing PRA and Σ'_n -induction and closed under (C1)–(C3). The proof of Theorem 4 uses the observation that:

$$(6) \quad PA' = \bigcup_n I\Sigma'_n.$$

The inclusion $\bigcup_n I\Sigma'_n \subseteq PA'$ is obvious. For the converse, it is easy to show that $\bigcup_n I\Sigma'_n$ contains PRA , contains induction for arbitrary \mathcal{L}' -formulae and is closed under (C1)–(C3). Thus $\bigcup_n I\Sigma'_n$ satisfies the closure conditions of PA' . Therefore it contains PA' .

Lemma 7 For all n , the theory $I\Sigma'_n$ is a conservative extension of $I\Sigma_n$.

Proof. Taking T to be $I\Sigma_n$, consider the translation $(\cdot)^*$ from \mathcal{L}' -formulae to \mathcal{L} -formulae defined in the proof of Proposition 1. We claim that for all \mathcal{L}' -formulae A , if $I\Sigma'_n \vdash A$ then $I\Sigma_n \vdash A^*$. The claim is shown by a straightforward modification of the proof of Proposition 1. The only additional case is to show that if A is an instance of Σ'_n -induction then $I\Sigma_n \vdash A^*$. But this holds because $(\cdot)^*$ maps Σ'_n -formulae to Σ_n -formulae, so A^* is an instance of Σ_n -induction. \square

Lemma 8 *For all n , the theory $I\Sigma'_n + R$ is a conservative extension of PA .*

Proof. By Theorem 3, $I\Sigma'_n + R$ contains PA . Let $(\cdot)^*$ be the translation used in the last proof. We claim that $I\Sigma'_n + R \vdash A$ implies $PA \vdash A^*$. We already know that if $I\Sigma'_n \vdash A$ then $I\Sigma_n \vdash A^*$ and hence $PA \vdash A^*$. So we need only show that $PA \vdash R^*$. However, as in the proof of Proposition 2, this follows from the following fact about PA [6]:

$$\text{for all } n, \quad PA \vdash \forall x (Bew_{I\Sigma_n}(\ulcorner A(x) \urcorner) \rightarrow A). \quad \square$$

By (6), it is clear that $PA' + R = \bigcup_n (I\Sigma'_n + R)$. It follows from Lemma 8 that $PA' + R$ is indeed conservative over PA . This completes the proof of Theorem 4.

5 Conclusions

In this paper we have investigated the potential of using the derivability conditions to induce properties of a provability predicate without having to go to the effort of following Gödel's construction. In particular we have focused on the possibility of obtaining non-conservative extensions using an extra axiom mimicking the uniform reflection schema.

Unfortunately, our results have been mainly negative. Although we have obtained a non-conservative extension in one notable case, the resulting theory, PA , can be obtained much more easily just by giving the full induction schema. Nevertheless, we believe that our results (both of non-conservativity and of conservativity) are interesting.

One natural question is whether a more general method of obtaining non-conservative extensions could be obtained by using more powerful axioms than $(C1)$ – $(C3)$. It is clear that the proof of Theorem 4 is general enough to apply to any T' generated by a collection of axioms based on arithmetically valid formulae of predicate provability logic (see [2]). Nevertheless, the possibility remains that a more general method could be obtained by going beyond the modal paradigm of provability logic (for example, by replacing $(C2)$ and $(C3)$ with single axioms quantifying over the Gödel numbers of formulae). We believe it to be an interesting programme to investigate such generalizations.

There are other ways of adding a new predicate to the language to obtain non-conservative extensions. For example, one can axiomatize the property of being a *satisfaction class* as in the work of Robinson, Kotlarski and others (see [5, Ch. 15]). Also, Feferman has obtained non-conservative extensions by axiomatizing a partial truth predicate [3]. It is unclear how such semantic approaches relate to the provability based approach of this paper.

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